

# Characterization of Transverse Beam Motion in Booster

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Fermilab

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# Measurement Procedure

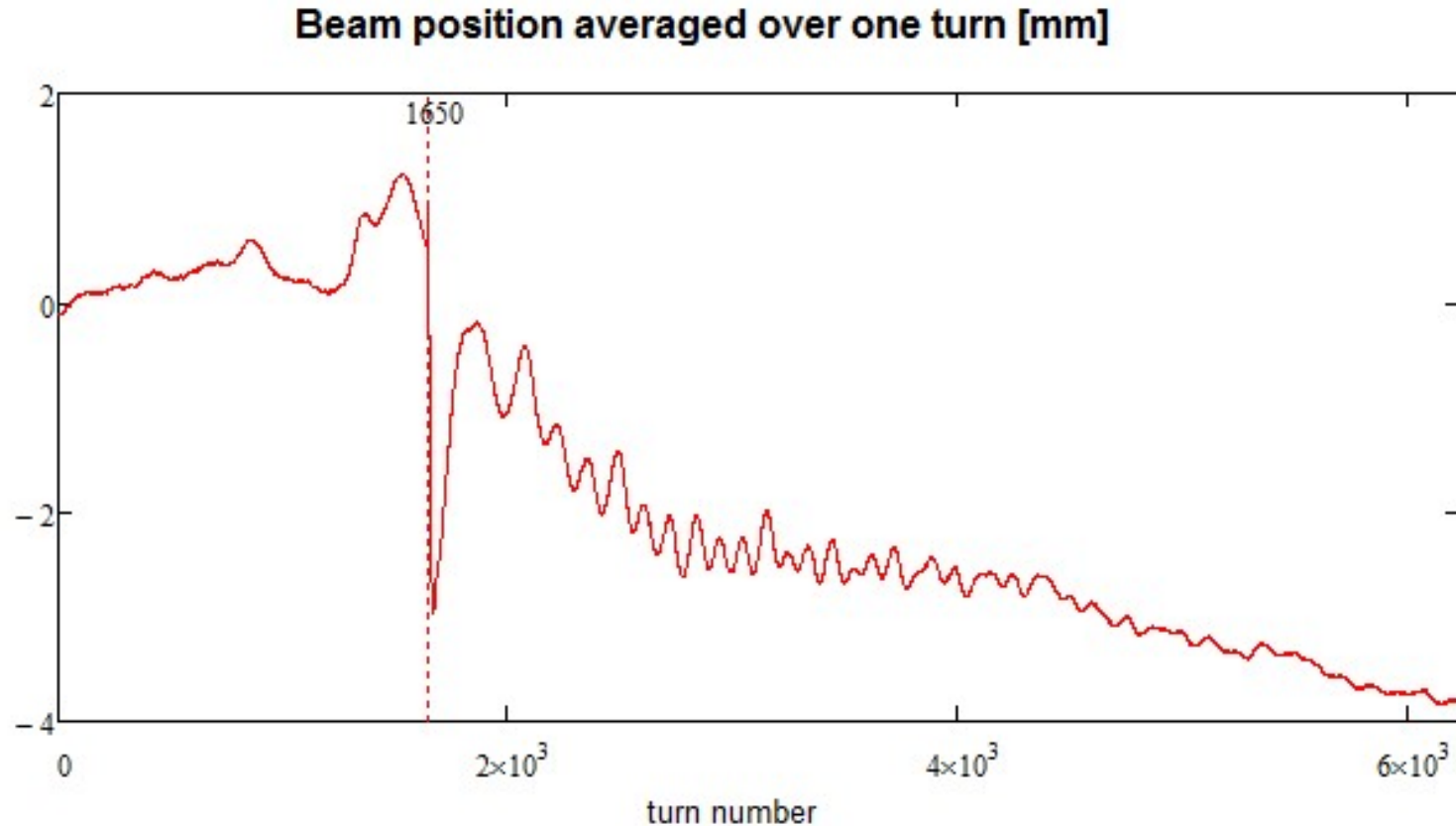
- Signals of damper pickups are digitized with 0.4 ns sampling time for about 1/3 of Booster cycle (6236 turns out of ~20,000) in the middle of accelerating cycle (covers transition crossing)
  - ◆ Hybrid is used to generate the sum and difference signals
    - Effective pickup radius (half aperture) -  $a=32$  mm
- Data for vertical and horizontal motions were acquired at different cycles
- Data processing
  - ◆ Boundaries for each RF bucket are found
  - ◆ Beam positions for each bunch are computed

$$x_n = A_n a \quad \text{where } A_n \text{ is computed using RMS fitting} \quad \vec{D}_n = A_n \vec{\Sigma}_n + C_n$$

- Presentation of data
  - ◆ Bunch positions turn-by-turn for each bunch
  - ◆ Bunch positions averaged over one turn
  - ◆ Spectra of bunch/beam motion
  - ◆ Dependences of longitudinal modes of relative bunch motion on time

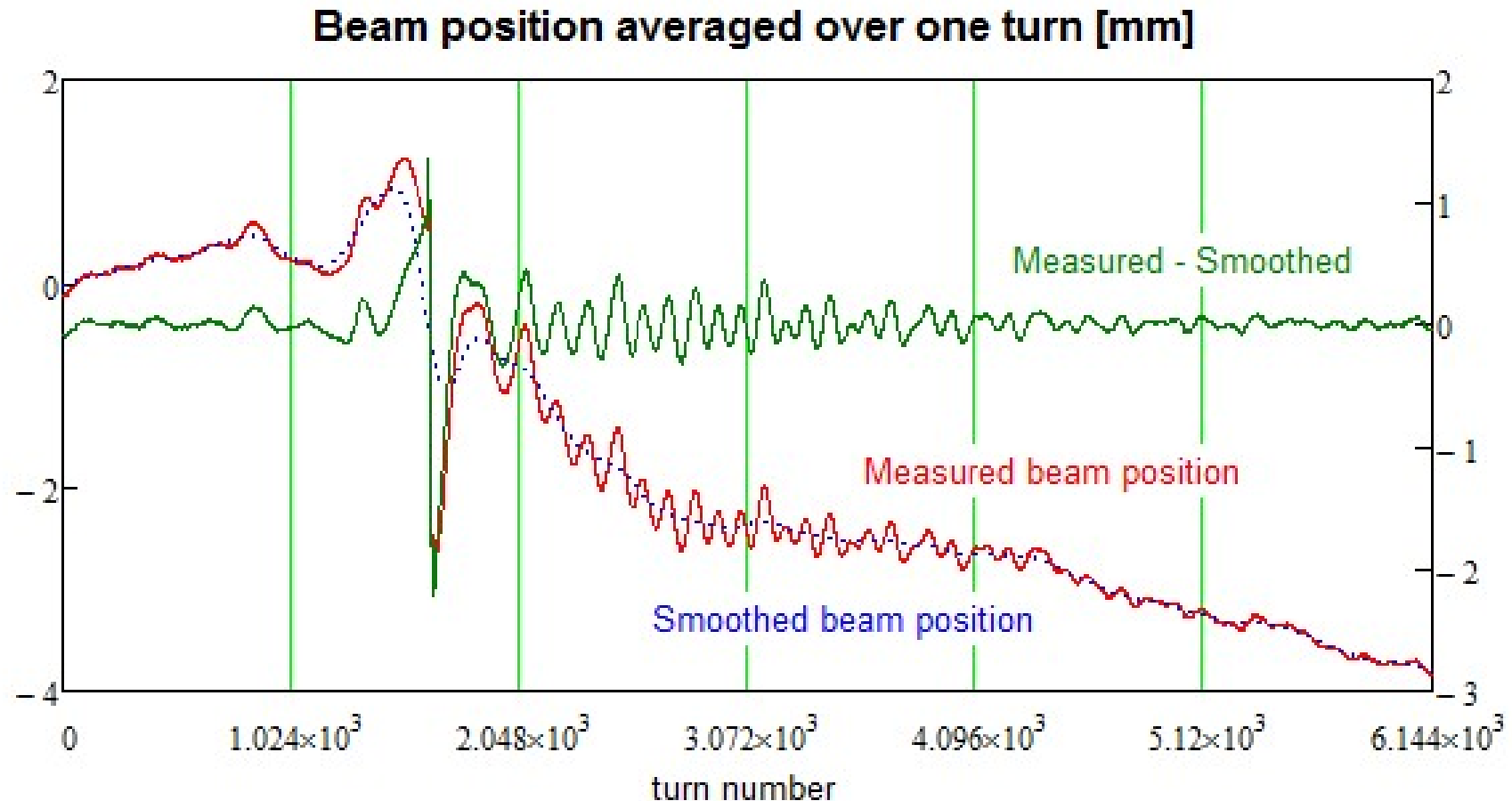
# Horizontal Bunch Motion Averaged over One Turn

- Positions of all bunches at a given turn are averaged (except the gap)



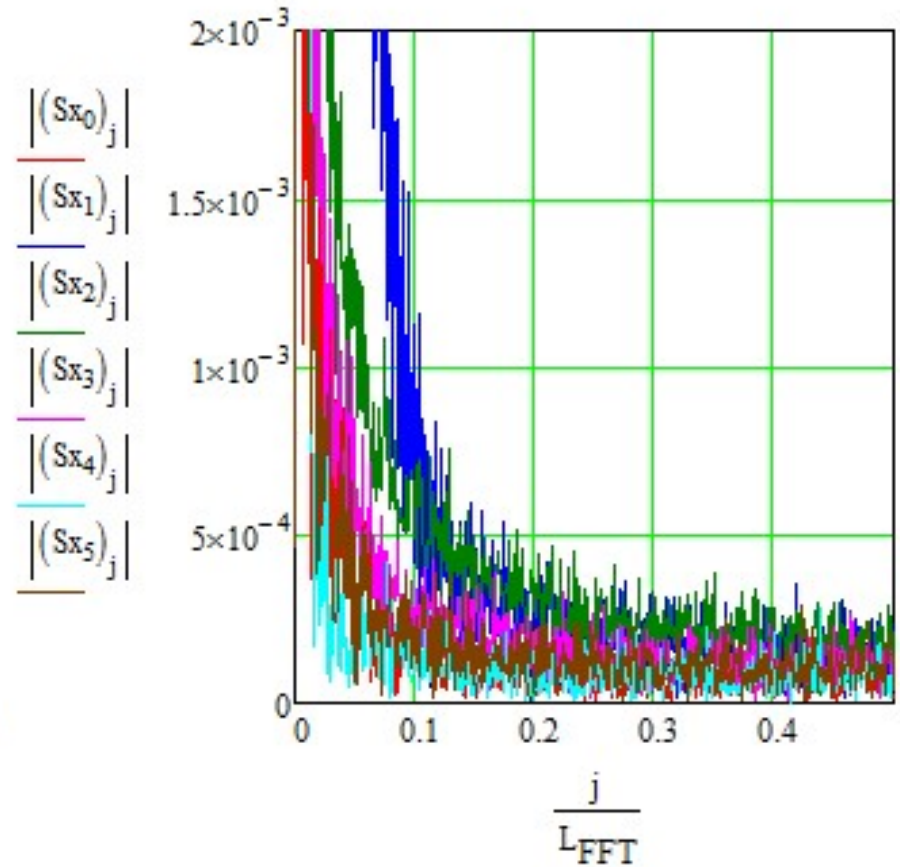
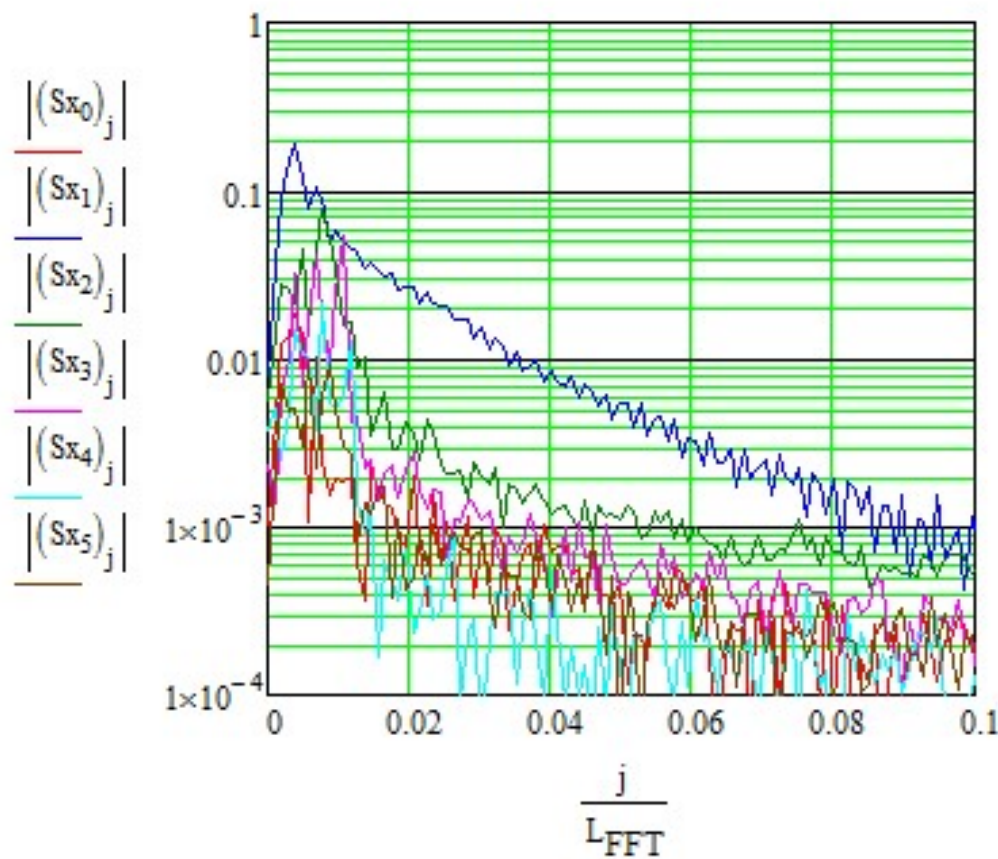
- Transition crossing is clearly seen at turn number of  $\sim 1650$  (counted from the beginning of data acquisition)
- Excellent accuracy of the beam position measurement:  
RMS deviation due to noise is about  $3\text{ }\mu\text{m}$ 
  - ◆ Digitization noise is the main source of errors (8 bit scope)

# Spectrum of Horizontal Beam Motion of All Bunches

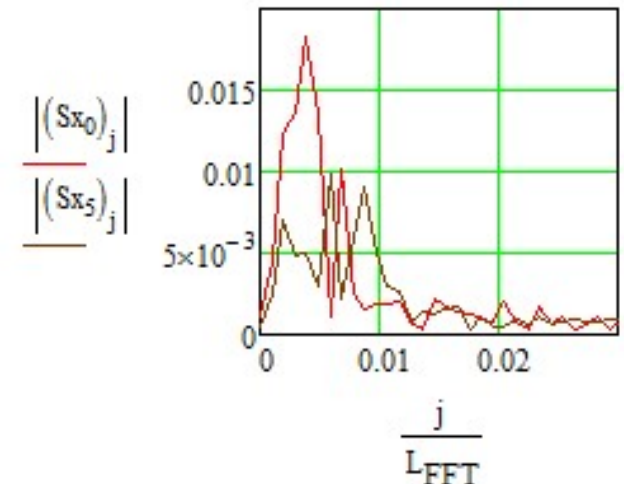


- To remove low frequency noise the smoothed beam motion was subtracted from its measured value
- All data were split in 6 regions
- FFT was done for each of 6 regions  
numbered 0 to 5; 1024 turns (points) per region

# Spectrum of Horizontal Beam Motion of All Bunches (2)

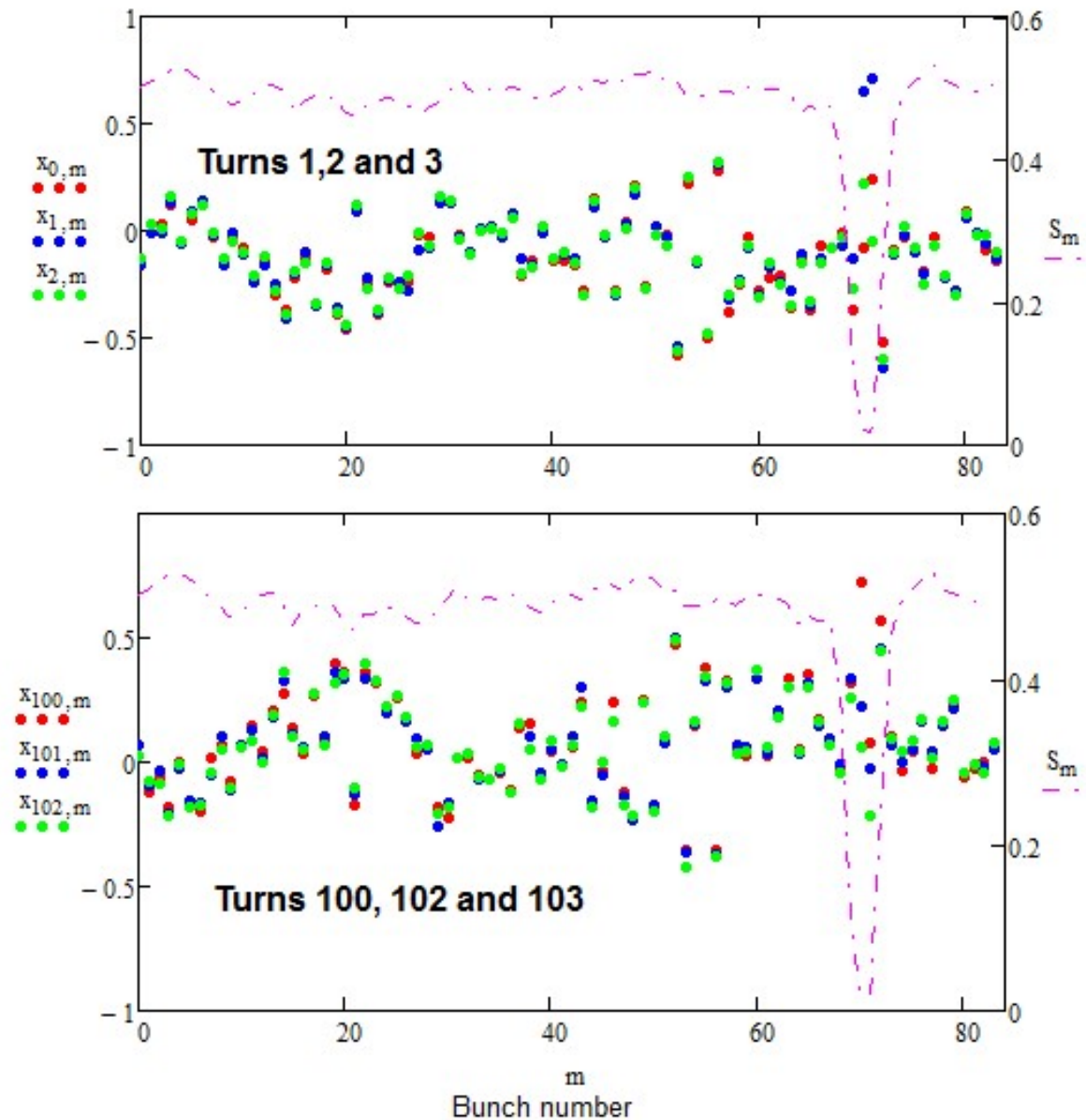


- Region 1 where transition crossing happens has significantly larger spectrum
- There is no measurable motion at the betatron frequencies. Low frequency motion  $Q < 0.015$  ( $f < 10$  kHz) is present with the rms values  $< 50 \mu\text{m}$



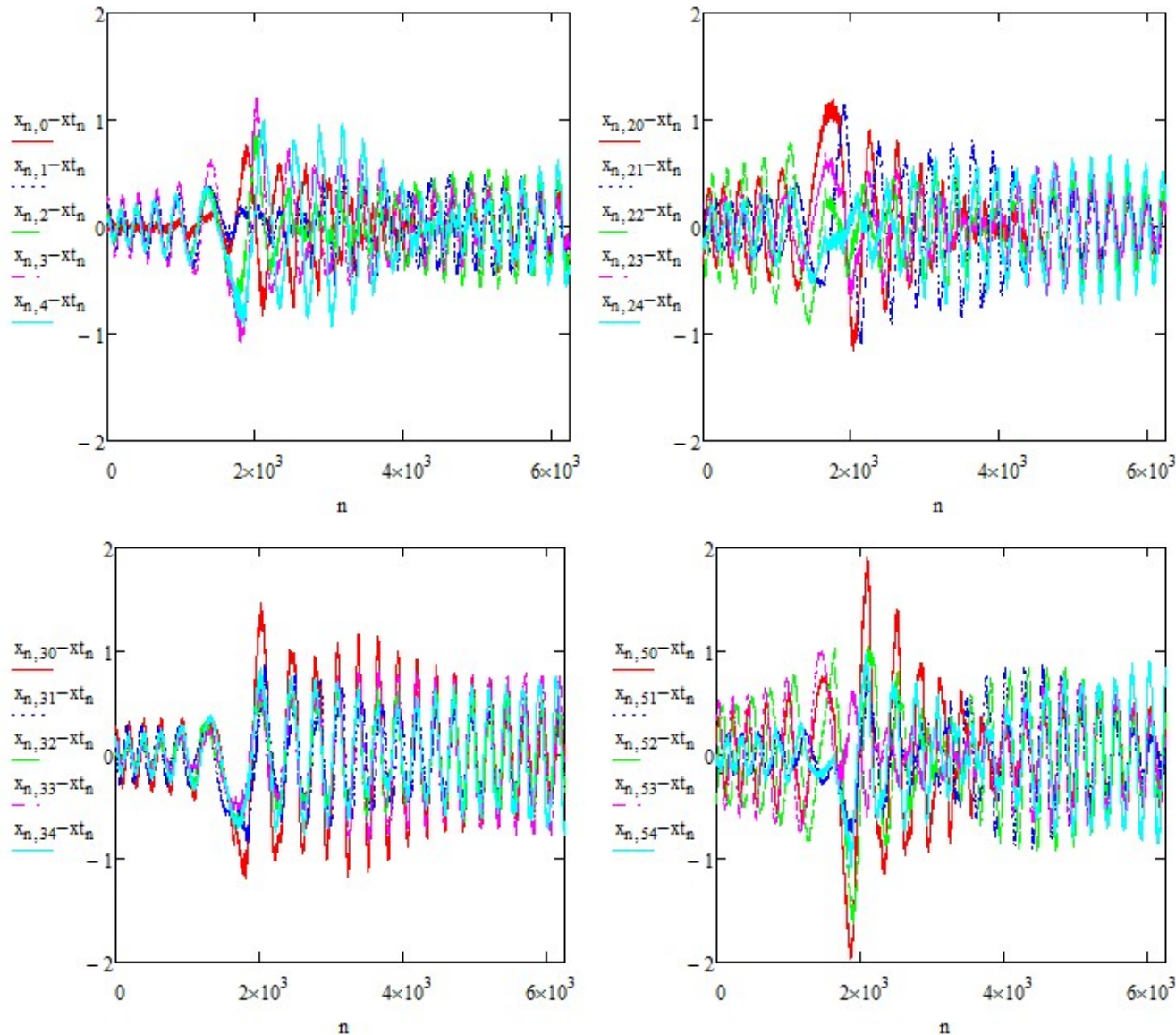
# Horizontal Motion of Separate Bunches

- There are considerable bunch displacements relative to the average beam position, about  $\pm 0.5$  mm
- Positions at nearby turns are close but changes significantly with time
- Many harmonics are present in bunch positions





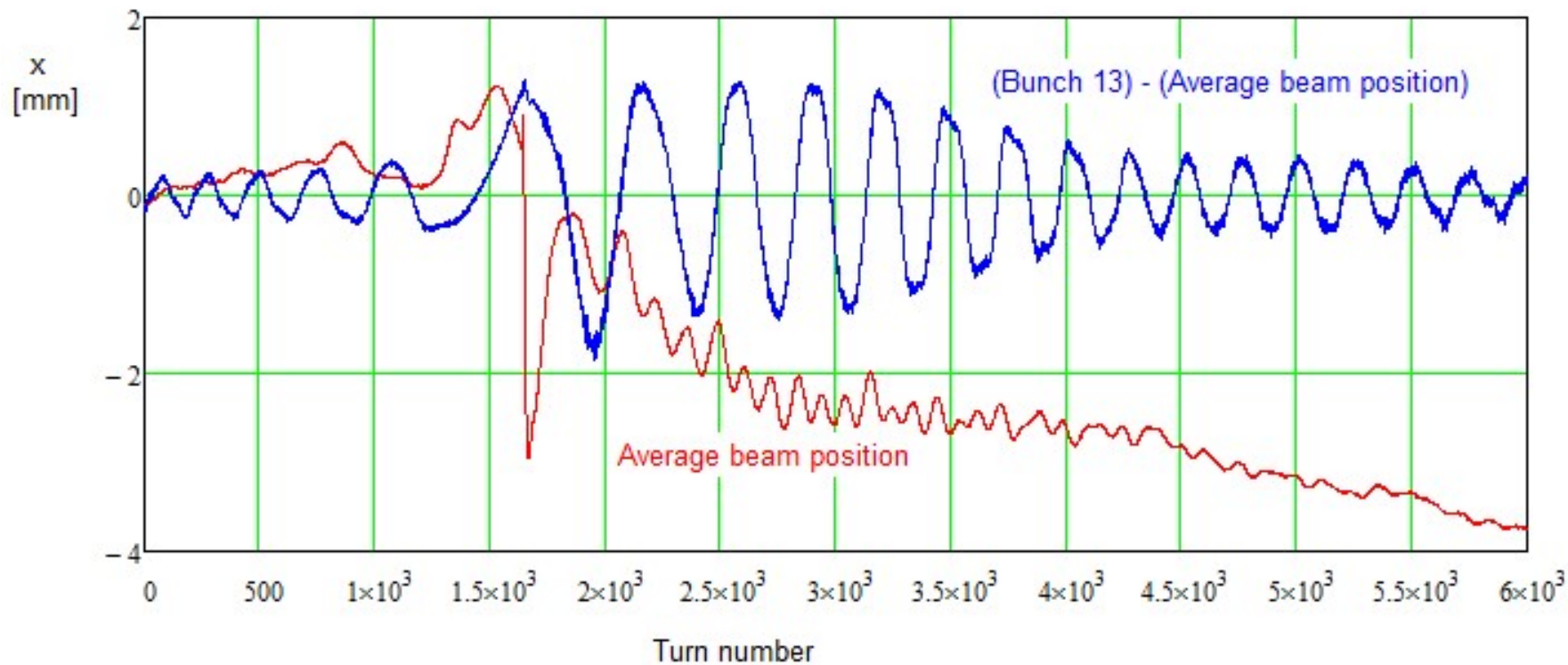
# Horizontal Motion of Separate Bunches (2)



*Bunch positions on the turn number relative to the average beam position for bunches 0-4, 20-24, 30-34, 50-54*

- Positions of bunches are oscillating at synchrotron frequency

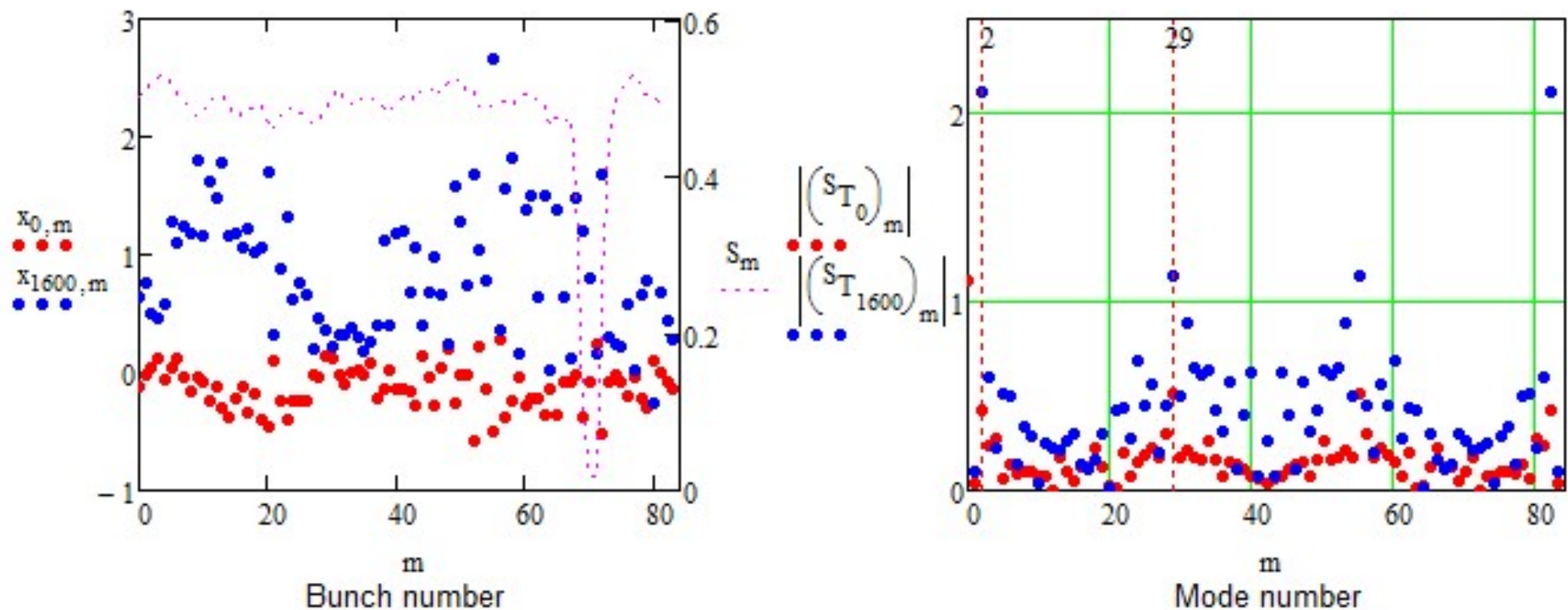
## Horizontal Motion of Separate Bunches (3)



- Bunches are moving at the synchrotron frequency relative to the average beam position
- The transition crossing excites motion of the average beam position
  - ◆ The motion is damped (LLRF certainly works)
  - ◆ Oscillations happen at frequency of longitudinal quadrupole motion
    - Approximately double synchrotron frequency
    - Frequency is shifted up by particle interaction (impedance)
    - Bunch length changes  $\rightarrow$  changes in bunch deceleration  $\rightarrow$  energy change

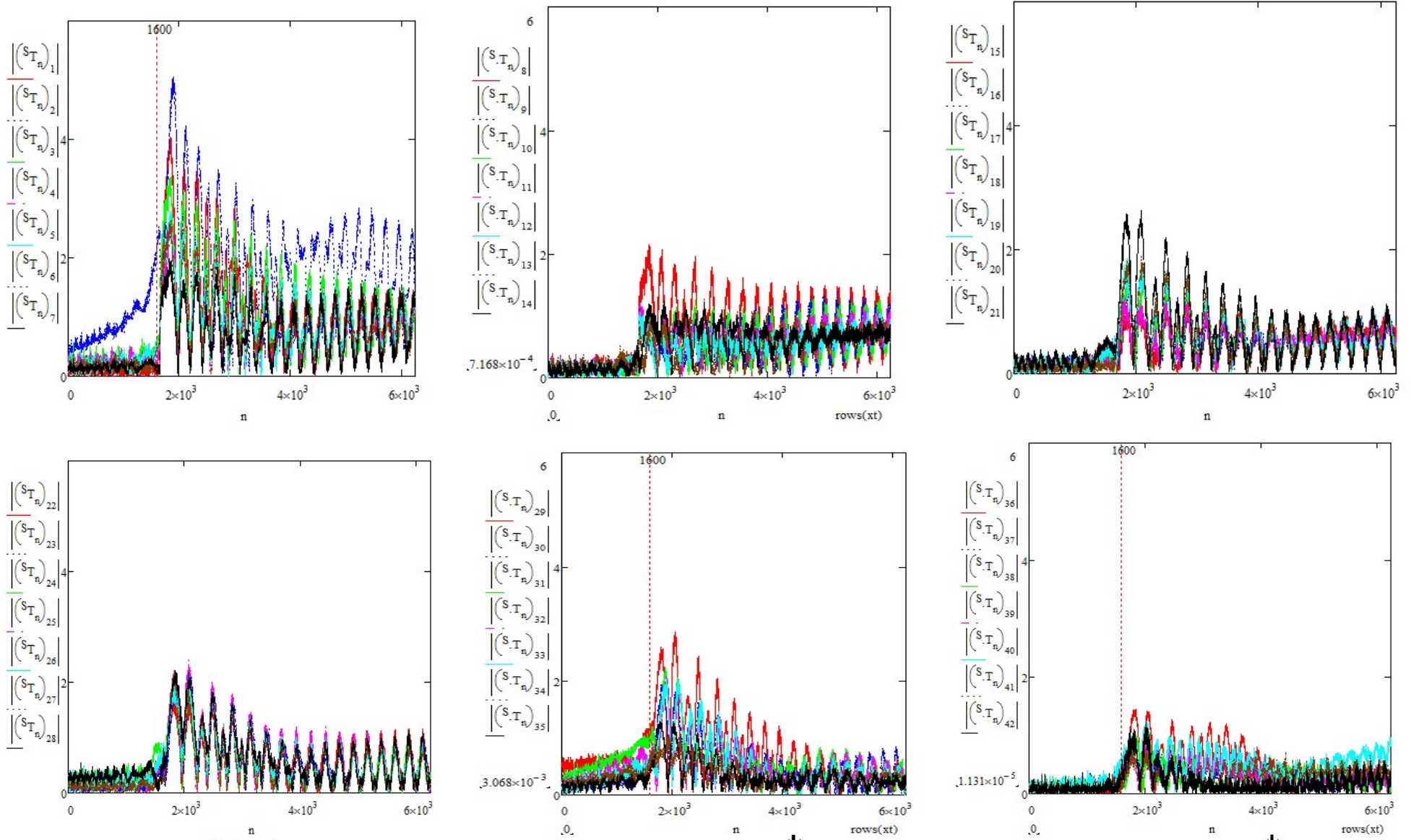


# Modes of Relative Horizontal Bunch Motion



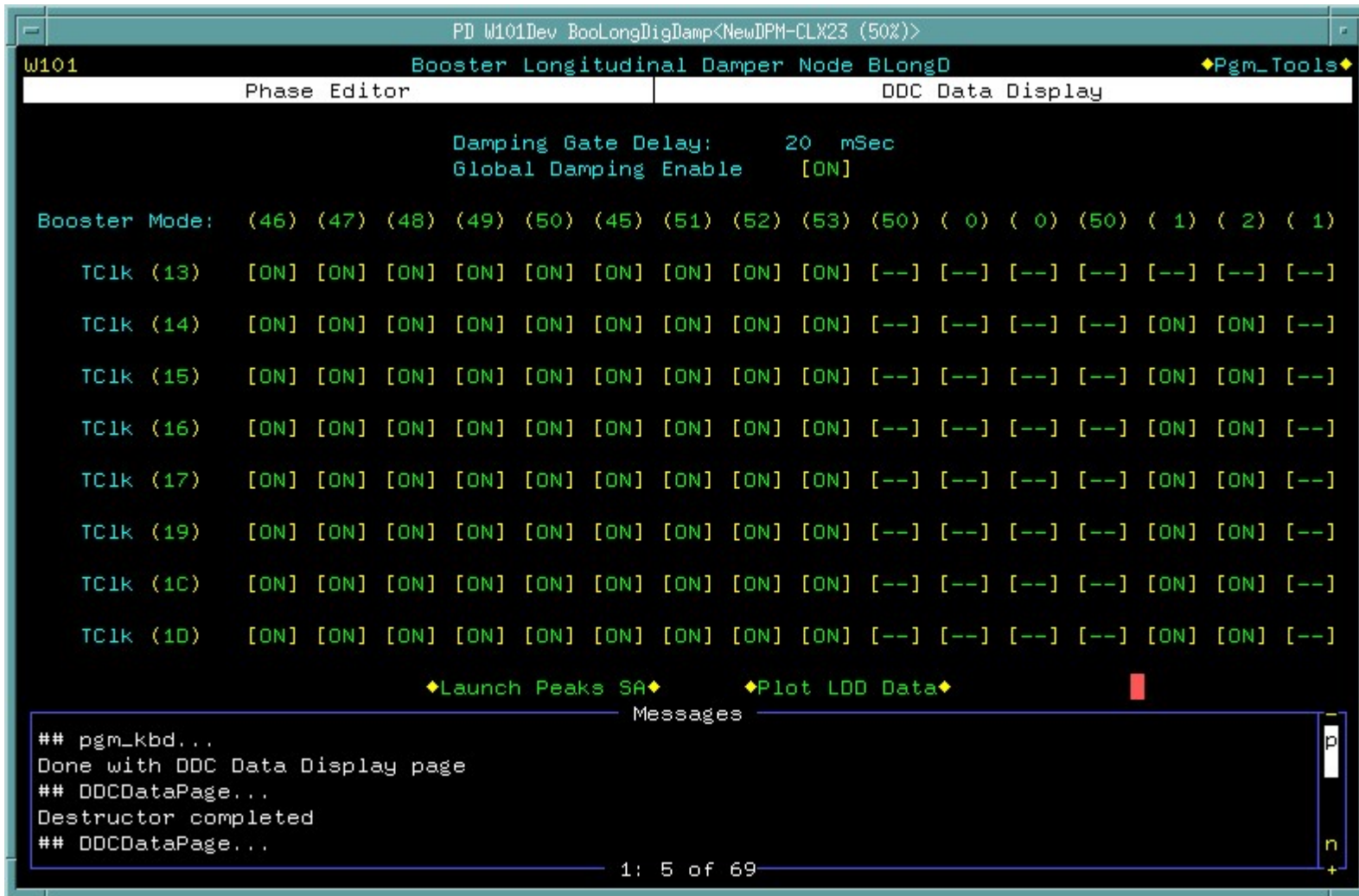
- Synchrotron motion results in energy variations which we observe as bunch position variations
- There are many harmonics in relative bunch motion
  - ◆ Modes 2 and 29 (or 80 and 55) dominate at both the turns 0 and 1600

# Modes of Relative Horizontal Bunch Motion (2)



- Modes 2 and 29 are most unstable before transition
- Mode 2 looks as a real problem and needs to be damped.

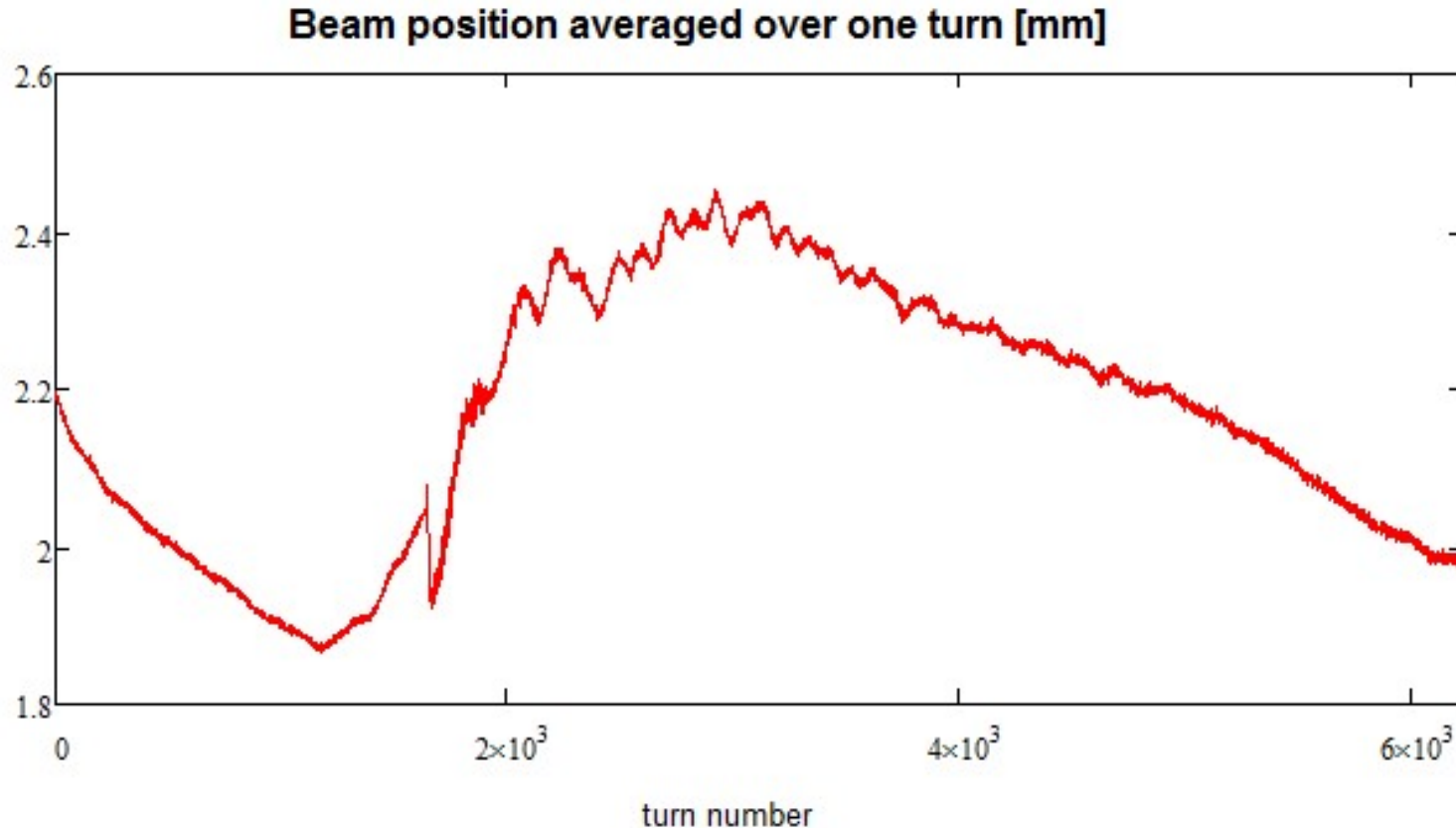
# Longitudinal Damper



Damped modes: 45=39, 46=38, 47=37, 49=35, 50=34, 51=33, 52=32, 1, 2

# Vertical Bunch Motion Averaged over One Turn

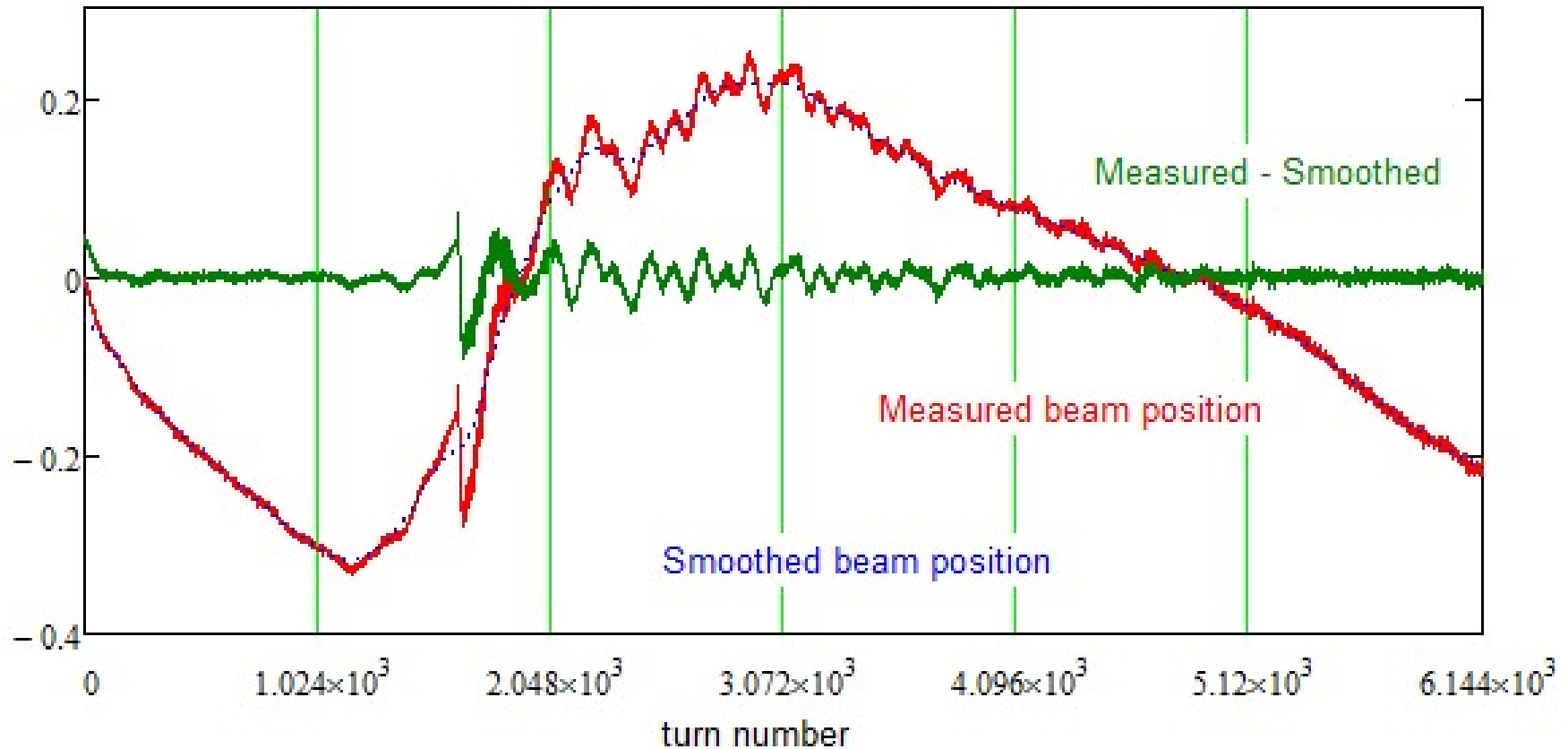
- Positions of all bunches at a given turn are averaged (except the gap)



- Transition crossing is also clearly seen at turn number of  $\sim 1650$  (counted from the beginning of data acquisition)
- Excellent accuracy of the beam position measurement: RMS deviation due to noise is about  $3 \mu\text{m}$ 
  - ◆ Digitization noise is the main source of errors (8 bit scope)

# Spectrum of Vertical Beam Motion of All Bunches

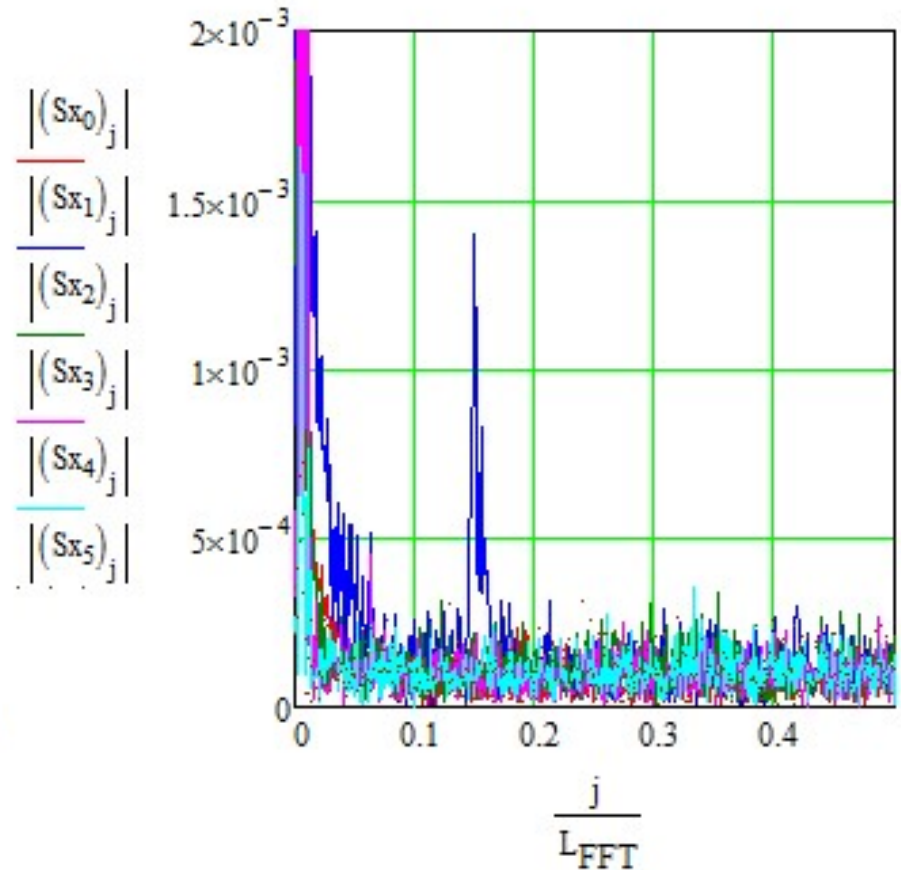
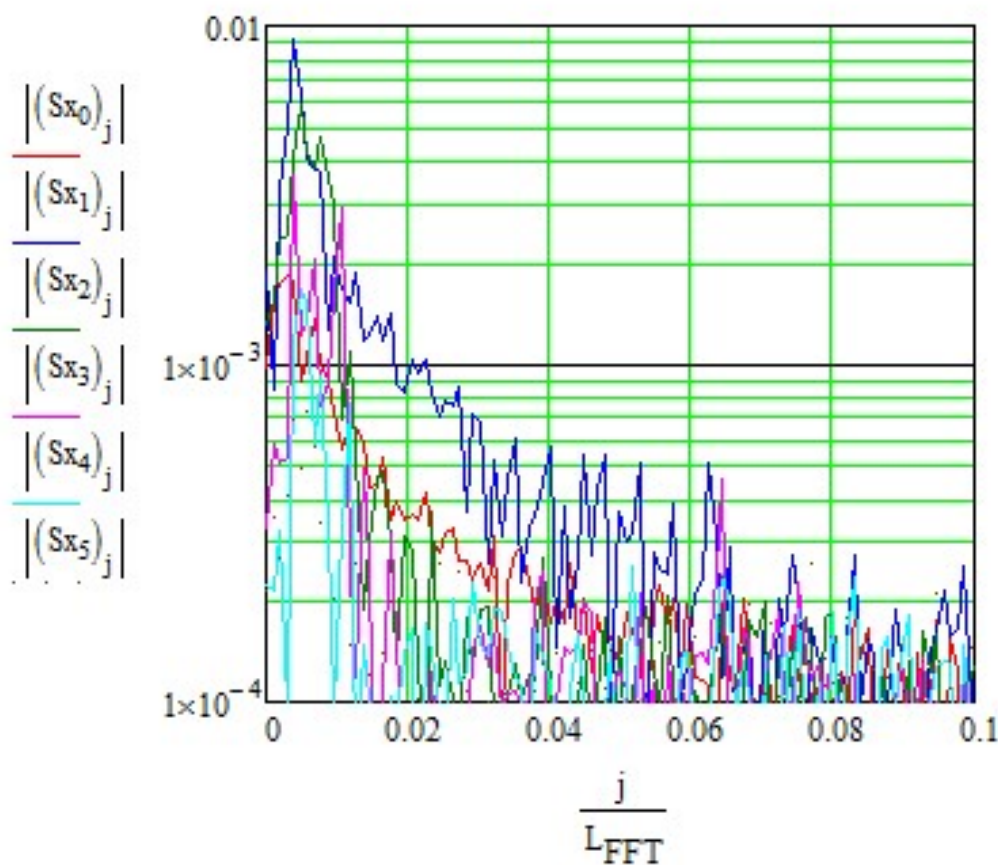
Beam position averaged over one turn [mm]



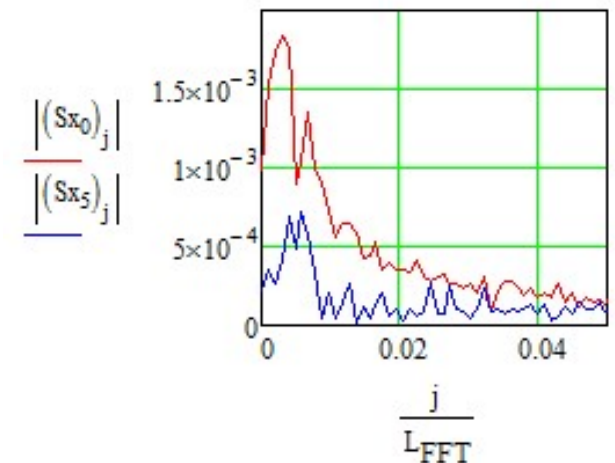
- To remove low frequency noise the smoothed beam motion was subtracted from its measured value
- All data were split in 6 regions
- FFT was done for each of 6 regions  
numbered 0 to 5; 1024 turns (points) per region



# ***Spectrum of Vertical Beam Motion of All Bunches (2)***

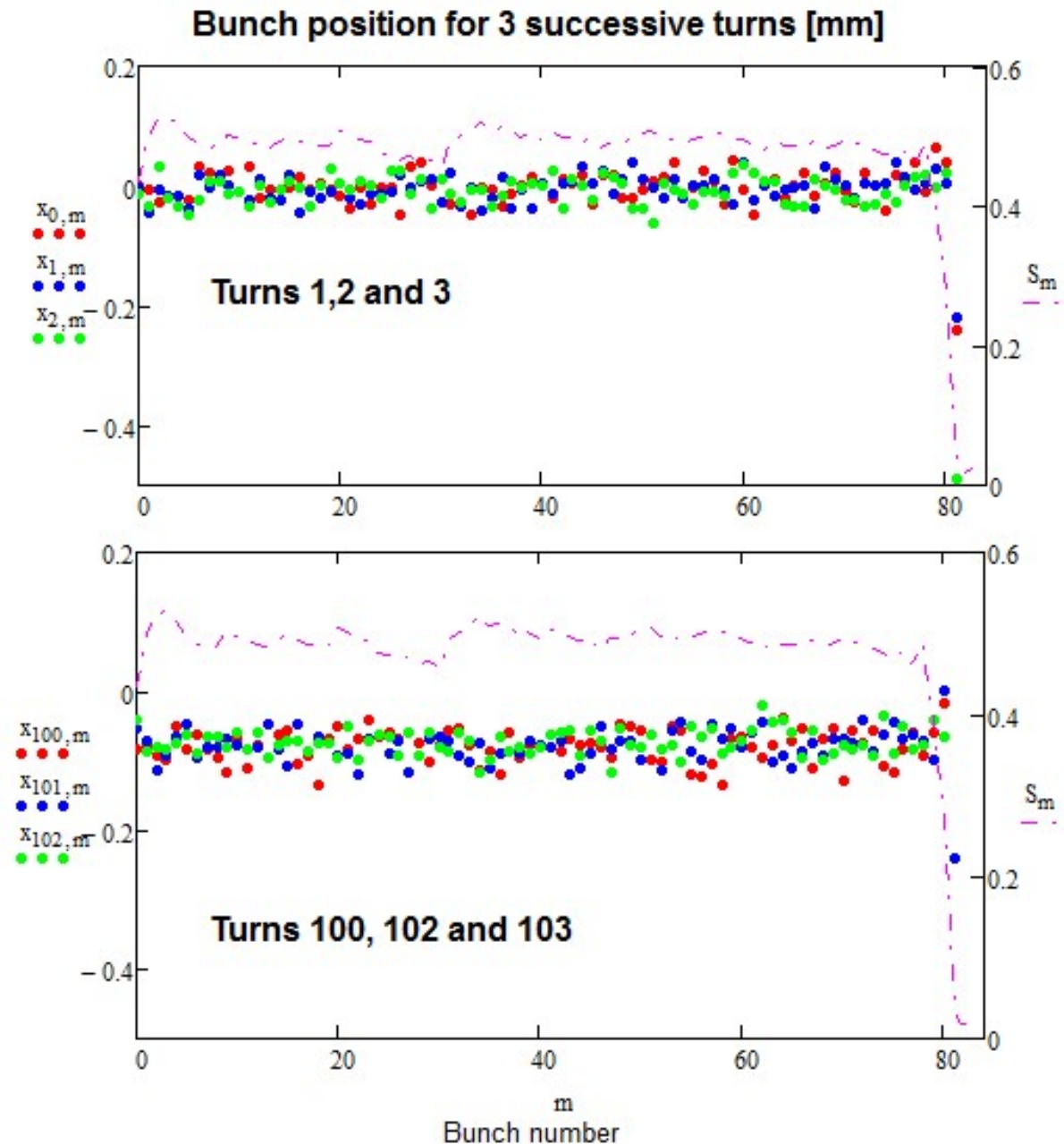


- Region 1 where transition crossing happens has significantly larger spectrum
- Transition excites the betatron motion; the betatron frequency  $\sim 0.85$
- Low frequency motion  $Q < 0.015$  ( $f < 10$  kHz) is present with the rms values  $< 10 \mu\text{m}$

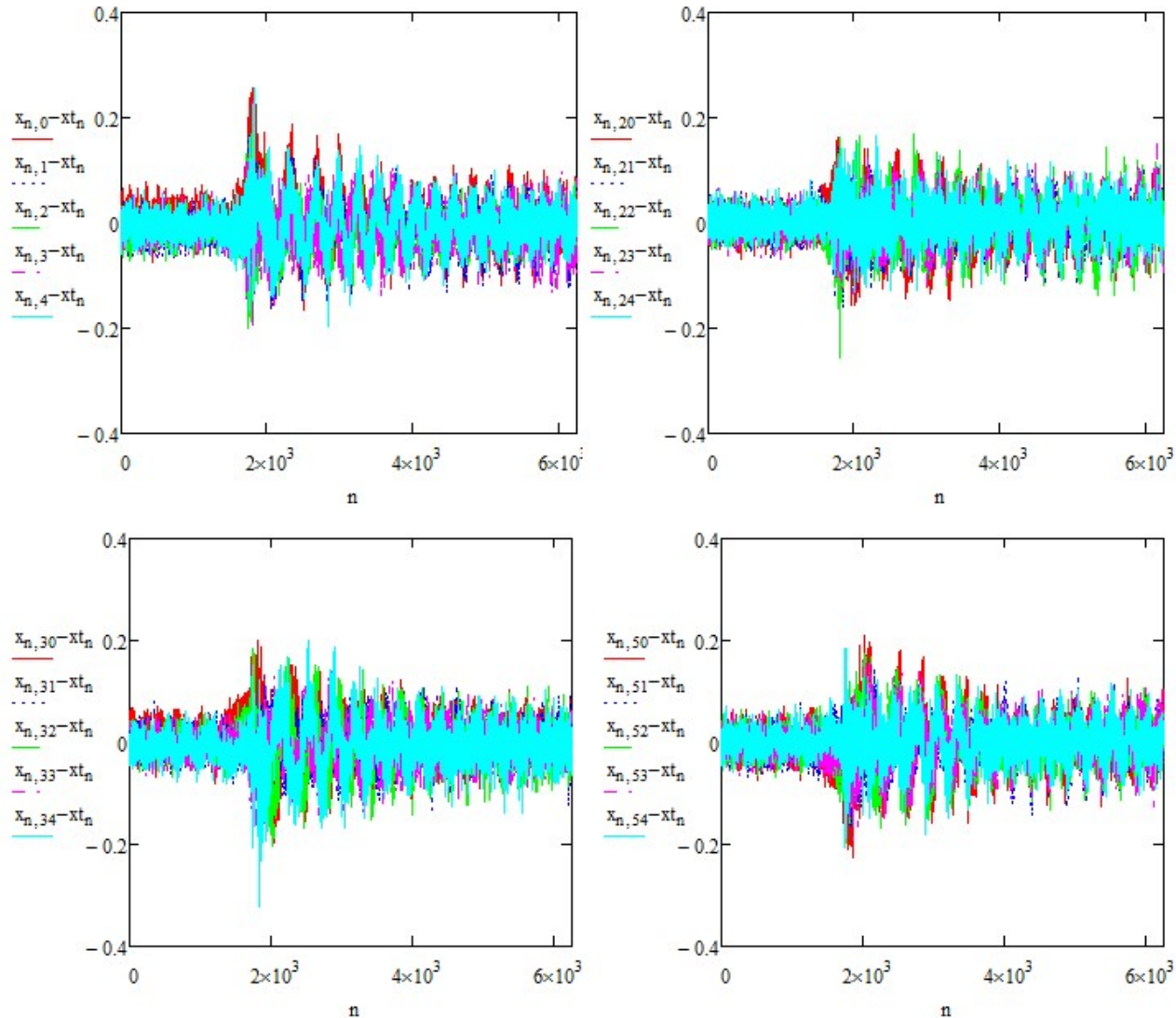


# Vertical Motion of Separate Bunches

- In difference to the horizontal plane there is no observable motion of bunches relative to the average position before transition



# Vertical Motion of Separate Bunches (2)



*Bunch positions on the turn number relative to the average beam position for bunches 0-4, 20-24, 30-34, 50-54*

- Transition excites oscillations at the synchrotron frequency with about 5 times smaller amplitude than for the horizontal plane

# Conclusions

- The scope measurements represent very accurate tool for bunch position measurement
  - ◆ 20 - 30  $\mu\text{m}$  rms accuracy for a single bunch
  - ◆ 2-3  $\mu\text{m}$  for average beam position per turn (80+ bunches)
- Measurements did not show any significant betatron motion due to ripple in magnets
  - ⇒ Ripple cannot drive any measurable noise
- There is horizontal motion of separate bunches relative to their center of gravity at synchrotron frequency
  - ◆ The amplitude is up 2 mm amplitude
  - ◆ It corresponds to the momentum changes  $\pm 10^{-3}$  ( $D=1.8$  m)
  - ◆ This is almost half of the rms maximum momentum spread near transition ( $\sigma_p \sim 2.5 \cdot 10^{-3}$ )
- The problem will be worse with intensity increase (measurements were acquired at nominal intensity)
- We have to look how to improve longitudinal damping and to move its switching on before transition crossing